4.3 High Heat Load X-ray Optics

4.3.1 Introduction

The issue of thermal management in optical components (mirrors and single-crystal monochromators) is one of the most challenging technical problems associated with the third-generation of hard x-ray synchrotron sources. Undulators placed on the straight sections of the APS storage ring can produce a total power in excess of 5 kilowatts and power densities in excess of 160 watts/mm^2 at a typical source-to-first-optic distance of 30 meters with 100 mA of stored beam. It is the job of the optics designer to develop components that can operate efficiently under the influence of these high heat load x-ray beams and that can deliver the x-ray beam to the experiment with the least possible loss in brilliance. Among other things, this means that the thermally induced slope errors must be reduced to well below the opening angle of the x-ray beam itself. The enormity of the task becomes quite evident when one considers that the radiation emitted from undulators at the APS has a vertical opening angle of only 15-20 microradians or about 3-4 arc seconds full width half maximum (FWHM).

At first, the problem may seem simply one of removing heat absorbed in the optics; however, removal of the deposited power is only one ingredient in the larger challenge of

controlling thermal distortions in precision optical components. When developing a thermal management plan for an optical component, one must consider not only the method of cooling (water, liquid metal, or cryogenic liquids flowing through slots, holes, or porous media, for example), but also the materials properties of the component (thermal conductivity, expansion coefficient, x-ray absorption), power deposition (quantity and apportionment), heat flow (magnitude and direction), and the resulting temperature distributions that will give rise to distortions of the component.

It was recognized early in the planning stages for third-generation hard x-ray synchrotrons that the power emitted by IDs, undulators in particular, might limit the quality of the monochromatic beam. In response, an impressive world-wide effort was mounted by researchers at many synchrotron facilities to find a solution. It is a credit to these laboratories that much of the research was complementary, with each devoting their effort to separate aspects and approaches contributing their own unique expertise to the problem. Here at the APS, impressive progress has been achieved with two approaches for high heat load crystal monochromators: cryogenically cooled silicon and room temperature diamond. A double-crystal monochromator, whose design was specified well before the optimal cooling approach had been finalized, has been successfully used for testing the various approaches. In addition to the progress made in crystal monochromators, a side-cooled mirror based on a design concept developed here has been installed and tested on one of the SRI-CAT ID beamlines and found to perform very well with little, if any, degradation in delivered beam brilliance, even under the highest power loadings.

4.3.2 Cryogenically Cooled Silicon Monochromators

Cryogenically cooled optics for use with high power synchrotron radiation beams were first suggested in 1985 for mirrors (Rehn, 1985) and in the following year for crystal monochromators (Bilderback, 1986). As was pointed out in those papers, the advantage of operating single-crystal-silicon optical components at cryogenic temperatures is twofold: (1) the thermal conductivity, k, increases by nearly a decade in going from room temperature to liquid-nitrogen temperatures, while (2) the coefficient of thermal expansion, , decreases from its room-temperature value of 2.6×10^{-6}/K, going through zero at 125 K, and then remains slightly negative near the boiling temperature of liquid nitrogen. Consequently, the thermal gradients and resulting strain are much lower in cryogenic silicon monochromators compared to room temperature silicon for a given set of conditions. (Any thermo-mechanical strain introduced into the crystal impacts the quality of the monochromatic beam.) A significant contribution that the APS has made to this field is the use of internally cooled optics, that is, optics with liquid nitrogen flowing through the component rather than in a contact-cooling arrangement in which the liquid nitrogen flows through a heat sink in good thermal contact with the optical component (Knapp et al., 1994, 1995). The internal-cooling approach provides more effective removal of power deposited in the optic than does the contact-cooling approach, thereby keeping the optic at an lower overall temperature. The primary technical difficulty to overcome when using this approach was the development of a vacuum-tight seal between the coolant manifold and the optical component that is radiation hard, withstands thermal cycling, and introduces minimal strain into the crystal.

This problem is exacerbated by the fact that the desired thickness of the diffracting crystal is typically less than one millimeter.

Our goal has been to develop cryogenically cooled silicon monochromator systems that will deliver near theoretical performance over the widest possible functional range of IDs at the APS. Because there is no standard monochromator design at the APS and there is an extended operational envelope, all of the monochromator, crystal, and cooling system designs were developed to have the widest possible range of applicability without major modifications, with the following general characteristics: high radiation resistance, high vacuum compatibility, ability to withstand thermal cycling, and no significant stress or vibration transmitted from the cooling manifold and piping to the optic. This comprehensive approach has worked. Of the 21 sectors currently under development at the APS, 17 have so far opted to use cryogenically cooled silicon monochromators on their ID beamlines. Several of these beamlines are currently operating routinely with liquid-nitrogen-cooled monochromators, providing high quality monochromatic beam for use in scientific experiments.

Almost all of the ID beamlines at the APS use an undulator as the primary source. Consequently, most of the development effort has been directed at designing optics for the undulator beamlines. Undulator radiation is an ideal candidate for the application of cryogenically cooled silicon crystals. By limiting the radiation striking the cooled optics to just the central cone of the undulator, the power incident on the crystal can be reduced from 5000 watts to about 700 watts, an important consideration because the capacity to remove large quantities of heat with liquid nitrogen is limited. The liquid nitrogen boil-off rate will also significantly decrease as the absorbed power is reduced. Absorbed power can be further reduced by designing the portion of the crystal where the beam strikes to be thin (in general <1 mm thick). The focus of our attention has been on the optimization of thin cryogenically cooled crystals for undulators; however, investigations have been made to measure the performance of thick silicon crystals on the APS undulator (see below) and at CHESS on a high power wiggler beamline.

The advantages of thin crystals are:

- Less absorbed power (and therefore less liquid nitrogen consumed)

- Smaller thermal gradients perpendicular to the diffraction surface

The disadvantages are:

- Heat must flow through a thin membrane rather than a full 3-D solid

- Fabrication is more difficult

- Crystals are more susceptible to mechanical strain

The advantages of thick crystals are:

- Easier to fabricate

- Crystals are less susceptible to mechanical distortions

- Cooling geometry is not as limited as for the thin case

The disadvantages are:

- Most of the x-ray power is absorbed (more liquid nitrogen consumed)

- Crystal heat exchanger must be larger

- Larger thermal gradients normal to the surface

One of the crystal designs that has been developed at the APS is shown with its coolant distribution manifold in Fig. 4.32. The thin element of the crystal is fabricated in a monolithic block of (111)-oriented silicon by milling slots in the top and bottom faces, leaving a region approximately one-half mm thick. A third slot is milled in the downstream face through which the transmitted beam passes. A maximum horizontal beam size of 2.5 mm can be accommodated, which includes essentially the entire central-cone radiation from the undulator. The downstream face of the crystal is visible, showing the slot through which the transmitted x-ray beam passes. Also shown is the array of coolant channels on either side of the diffraction element. The seal between the Invar manifold and the silicon is made via In-coated metal C-rings. Sealing pressure is maintained by using Belleville® spring washers on the clamping screws. The mounted crystal assembly is supported on a kinematic plate
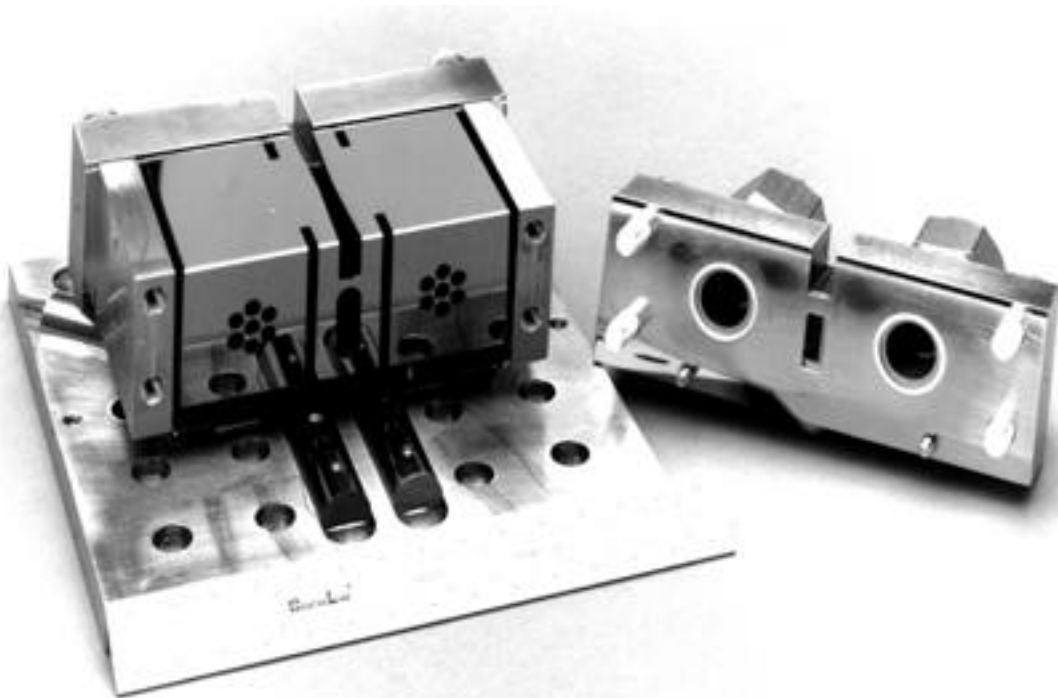
Fig. 4.32 Photograph of the cryogenic, thin silicon crystal and its coolant manifold, which have been tested on an undulator beamline at the APS. The x-ray beam impinges on the bottom of the slot cut into the top surface of the crystal. Visible is the downstream face, showing the slot that allows the transmitted beam to pass through the crystal, and the coolant channels on either side of the diffraction element.

that allows for unconstrained thermal expansion while preserving the absolute position of the thin diffraction element relative to the x-ray beam.

In the summer of 1995, this crystal was first tested on an APS undulator beamline (Rogers et al., 1996b). The beam passed through a temporary commissioning window consisting of 0.50 mm of graphite, 0.17 mm of CVD diamond, and 0.50 mm of Be and slit to limit the beam on the crystal to 2.0 mm horizontal × 2.5 V mm vertical. (About 12% of the total beam power was absorbed in the window assembly at an undulator gap of 11.1 mm.) A broadening of the rocking curve widths is the signature of thermal distortions. Because the thermal broadenings are expected to be small, on the order of arc seconds, a higher-order reflection is monitored, in this case the (333). Rocking curves as a function of photon energy are shown in Fig. 4.33 for a fixed undulator gap of 11.1 mm corresponding to a deflection parameter, K, of 2.57. This situation simulates far worse heat loads than would normally be encountered because the undulator gap was kept at 11.1 mm, corresponding to a first harmonic energy of 3.27 keV, for all of the rocking curves and was not opened to track the harmonic as the diffracted photon energy was increased, which would normally be the case. As the gap is opened, the power rapidly decreases. For example, for a first harmonic energy of 8 keV, corresponding to a gap of about 18.3 mm, the incident power and peak power density are only about 40 percent of that at a gap of 11.1 mm. Consequently, for typical operation in which the gap (i.e., harmonic) is matched to the diffracted photon energy, the monochromator should perform equally well at much higher currents. The nearly constant width of the (333) reflection as a function of energy is due not to thermal strain but rather to fabrication/mounting strain.
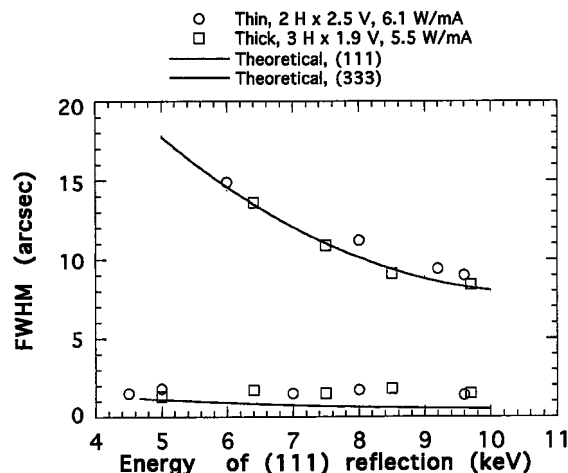

Fig. 4.33 First- and third-order rocking curve widths (FWHM) as a function of photon energy at a fixed undulator gap of 11.1 mm. The energy of the x-rays diffracted by the (333) planes is three times the abscissa value. The beam incident on the thin crystal measured 2.0 H × 2.5 V mm² with a power of 6.1 W/mA, and the beam on the thick part of the crystal measured 3.0 H × 1.9 V mm² with a power of 5.5 W/mA. The storage-ring current ranged from 61 to 96 mA for the thin-crystal data and from 89 to 95 mA for the thick-crystal data.

The performance when the beam was allowed to strike a thick portion of the crystal is also displayed in Fig. 4.33. The thick crystal data were taken from the top surface of the monochromator crystal laterally adjacent to the diffraction slot of the thin element. Obviously, the cooling geometry for the thick crystal data is not optimum because the heat flows predominantly to only one set of coolant channels; the other set is thermally isolated by the diffraction slot. Nonetheless, the thick crystal performed much better than our expectations and actually exhibited narrower rocking curves than the thin part of the crystal. This is due primarily to the lower mechanical strain in the thicker portion of the crystal.

Similarly designed, cryogenically cooled, thin silicon crystals were tested at the European Synchrotron Radiation Facility (ESRF) using the focused wiggler radiation available on beamline BL3 (Rogers et al., 1995, 1996c). Data collected at a fixed energy as a function of incident power for the thin (0.6 to 0.7 mm) portion of the crystals and for the thick (>25 mm) part are shown in Fig. 4.34. The mechanical strain in the thin parts of about 2 arcsec dominates the contribution from the thermal strain, and, therefore, the thermal component is not clearly resolvable. A slight broadening trend of the rocking curve for the thick part of the crystal is discernible as a function of absorbed power. The rocking curve for the thick section broadened to 1.7 arcsec at the highest incident heat flux, which corresponds to a normal incidence average power density of 521 W/mm^2. (The numbers on the x-axis of Fig. 4.34 take into account the spreading of the power density because of the Bragg angle of 11.4°.) This incident power density is in excess of what is expected for the APS undulator A in closed-

gap operation (first harmonic at 3.27 keV) at a storage-ring current of 300 mA.

4.3.3 Liquid-Nitrogen Pumps

A liquid-nitrogen pumping system is required for each monochromator. The pumping system supplies pressurized liquid nitrogen at a variable flow rate to the optic, where it removes the heat absorbed by the optic from the x-ray beam. The pumped liquid nitrogen then returns to the pumping system where the heat is rejected to an internal bath of atmospheric liquid nitrogen. The boiled-off liquid nitrogen is intermittently replaced from either a local or a remote storage tank or the gas is condensed in a local nitrogen reliquefier and returned to the pumping system. The pumping system is capable of handling a heat load of at least 3 kW. It supplies a variable flow rate of up to 20 l/min at a system pressure of up to 150 psig.

The APS has expended considerable effort in developing the technical requirements for the liquid-nitrogen pumping systems to ensure that they are adequate for all of the proposed uses at the APS. The system is compact enough to be housed within the first optics enclosure next to the monochromator. The transfer hose connections are of a standard design compatible with all of the various monochromators in use at the APS. The system is wired for computer control and monitoring. Oxford Instruments has developed a commercially available pumping system based on technical specifications developed by XFD scientists and engineers, and has supplied 16 such pumping systems to APS CATs. The Oxford pumping system installed on Sector 1-ID is shown in Fig. 4.35. Several of the Oxford systems
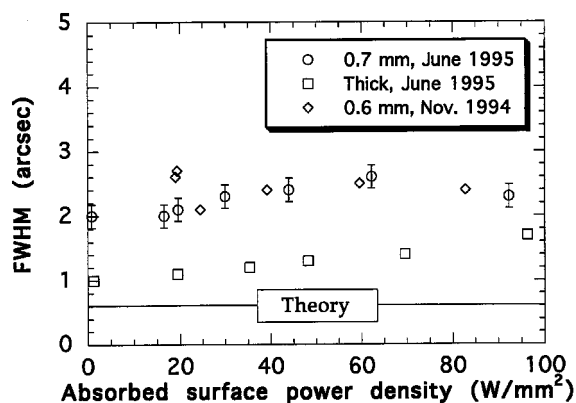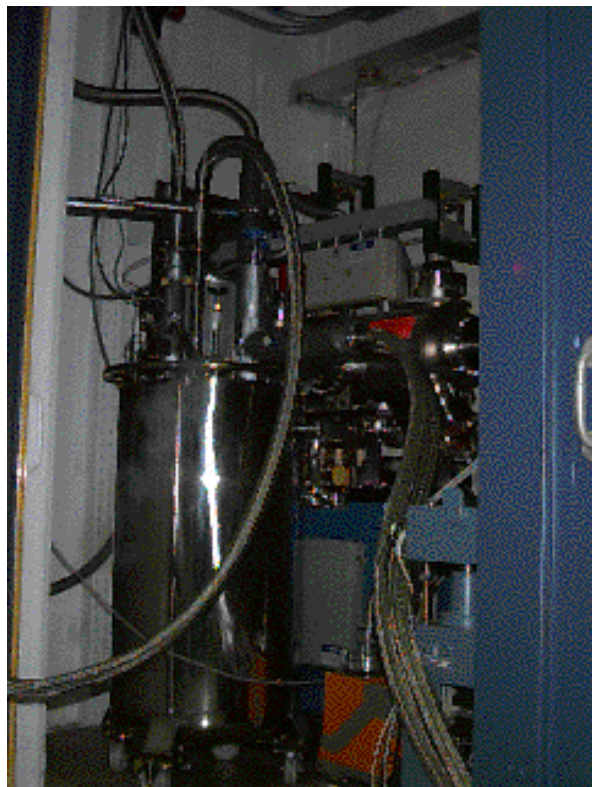

Fig. 4.34 Rocking curve widths (FWHM) for the Si (333) reflection at 30 keV as a function of absorbed power density on the surface of the crystal. Data are shown for both thin and thick crystals. The error bars are shown only for the first data set but are the same for all.

Fig. 4.35 Photograph of the liquid-nitrogen pumping system installed in the FOE of Sector 1-ID.

have been operating for almost 2 thousand hours with no pumping system failures. The uniformity of design allows for standardization of components and inter-CAT sharing of resources, providing for the greatest possible flexibility and reliability of the cooling systems at the lowest cost.

4.3.4 Water-Cooled Diamond Monochromators

Water-cooled diamond single crystals provide an alternative to cryogenically cooled silicon monochromator crystals. At room temperature, the thermal conductivity of diamond is about ten times larger than that of silicon, while the linear expansion coefficient of diamond is two times smaller than that of silicon. For the same absorbed power and

cooling geometry, we expect that the temperature gradients and the thermal distortions in diamond will be considerably less than in silicon. Another advantage of using diamond is that, due to its lower atomic number, the absorption of x-rays in diamond is less than in silicon: a 0.25-mm-thick diamond crystal will absorb 17% of 8 keV x-rays, while a silicon crystal of the same thickness will absorb 97%. Thus, a thin diamond crystal will absorb a smaller fraction of the incident synchrotron beam, with considerably smaller thermal gradients and strains, compared to a similarly cooled silicon crystal (Blasdell et al., 1995).

One disadvantage of diamond monochromators is the reduction in delivered flux compared to a silicon monochromator. For energies above 6 keV, the photon flux delivered by a double-crystal diamond (111) monochromator will be about half the flux from a silicon (111) monochromator. The reduction in flux is due to the smaller Darwin width and lattice constant, which result in a narrower energy bandpass. The decrease in flux may be an acceptable trade-off when the ease of cooling a diamond crystal is considered and/or when beams with a narrow energy width are required. Another drawback of using diamond crystals is the current unavailability of perfect single crystals of appropriate size. The largest commercially available plates at this time are 7 mm by 5 mm.[1] These plates are cleaved from synthetic type 1b stones and exhibit several arc seconds of mosaic spread and/or strain.

Thermal tests of the diamond were made in a double (diamond) crystal monochromator arrangement on the Sector 1 ID beamline,

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[1] Grown by DeBeers and available in the U.S. through Harris Diamond Corporation, Mount Arlington, New Jersey.

using x-ray beams produced by the 2.4-m-long undulator A. The single-crystal plates were manufactured by Drukker International, from synthetic stones grown by De Beers, and they were supplied by Harris Diamond Corporation. Two sets of diamond plates were tested; the first set was 6 mm by 5 mm in size, with one 0.25-mm-thick crystal and one 0.37-mm-thick crystal, and the second set was 7 mm by 5.5 mm in size with both crystals 0.44 mm thick. The quality of the diamonds was assessed off-line by taking x-ray topographs at 8 keV. The data indicate that the crystals are not perfect and that the mosaic spread/strain is of the order of 5 or 6 arc seconds over the full face of the plates. While the added strain can result in a loss of brilliance in the diffracted undulator beam, it can also increase the bandpass for applications in which the flux is important, thus making up for some of the loss in throughput compared to a Si (111) monochromator.

The initial diamond thermal tests were performed with the set of smaller diamonds, with the first crystal straddling a 2-mm-wide trough on a water-cooled, nickel-plated copper mounting block (see Fig. 4.36). For the second set of tests with the slightly larger diamonds, the trough in the copper mounting block was increased to 3 mm. In both cases, the thermal contact between the diamond and the copper was achieved by using a thin layer of Ga/In eutectic (80% gallium, 20% indium); the crystals were held in place by the surface tension of the eutectic layer. The white-beam size at the first crystal position was 1.4 mm horizontal by 1.8 mm vertical for the first run, and 2 mm horizontal by 1.2 mm vertical for the second run. The first crystal diffracted 62% and 83% of the undulator central cone of radiation in the horizontal plane for the first and second runs, respectively, and over 97%
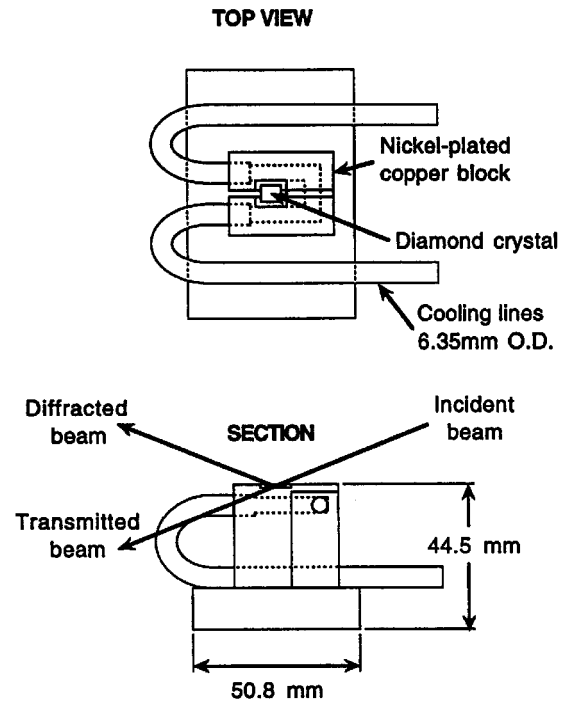

Fig. 4.36 Top view and section of the water-cooled first crystal mount of our diamond double-crystal monochromator. The copper block was nickel plated to prevent the diffusion of the Ga/In eutectic into the copper. The trough in the block allows the transmission of the incident x-ray beam.

in the vertical plane in both cases. Rocking curves of the two diamonds were collected, and the widths of those curves were used to gauge the thermal distortion of the first diamond. As with the silicon tests, the (333) reflections were monitored for thermally induced strain because their widths are narrower than those of the first-order reflection.

Figure 4.37 shows the FWHM of the rocking curve of the diffracted beam as a function of energy for the (111) and (333) reflections taken at two energies, 6.2 and 9.7 keV, for the first set of diamonds. Also shown are the
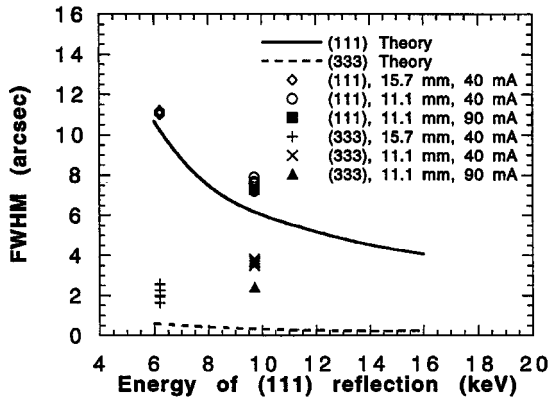
Fig. 4.37 Calculated and measured value for the FWHM of the diamond double-crystal rocking curve as a function of energy of the x-rays diffracted from the (111) planes. Data were taken simultaneously for the (111) and (333) reflections; the energy of the x-rays diffracted by the (333) planes is three times the abscissa value. The spread in the data is primarily due to diffraction for different regions of the imperfect diamond crystals and not to thermal effects.
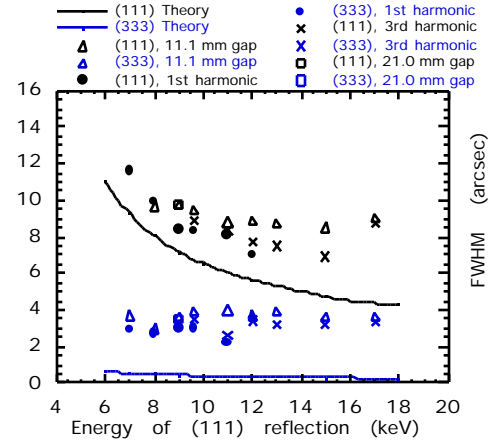

Fig. 4.38 Calculated and measured values for the FWHM of the diamond double-crystal rocking curve as a function of energy of the x-rays diffracted from the (111) planes. Data were taken simultaneously for the (111) and (333) reflections; the energy of the x-rays diffracted by the (333) planes is three times the abscissa value. The storage-ring current ranged from 77 to 86 mA. For a given energy, the gap setting of the third harmonic data point is smaller than that of the first harmonic point; the smallest reachable undulator gap was 11 mm.

theoretical double-crystal rocking curve widths, calculated for perfect single-crystal diamonds. The maximum power incident on the first crystal was 200 W, with a power density of 108 W/mm^2 (normal incidence), at 11.1 mm gap and 90 mA. Data at more energies were collected with the second (larger) set of diamonds (see Fig. 4.38). In this case, data were collected for a fixed undulator gap (11 mm) and at gaps such that the diffraction energy corresponded to either the first or third undulator harmonic. The maximum power and power density (normal incidence) incident on the first crystal were 280 watts and 123 W/mm^2, respectively, at 11 mm gap and 86 mA. The corresponding maximum power and power density absorbed by the first diamond were 37 watts and 16 W/mm^2, at 17 keV. The scatter in the

measured FWHM of the rocking curves is attributed to small beam motions and the extreme sensitivity of the measurements to the position of the beam due to the less-than-perfect crystalline quality of the diamonds. Nonetheless, these data are encouraging from a thermal point of view, because there are no evident thermal distortions, that is, there is not an obvious increase in the width of the (333) rocking curve as a function of closing undulator gap and increasing ring current. We notice that the discrepancy between calculated and measured widths is larger for the higher energy, when the footprint of the beam on the crystals is larger and a larger portion of the imperfect diamond is being sampled.

Also of interest is comparison of the flux through our diamond (111) monochromator and a silicon (111) double-crystal monochromator. Using the same beam size and undulator gap, we measured the maximum intensity of the (111) reflection at 6.2 and 9.7 keV with the smaller set of diamonds and a cryogenically cooled Si (111) monochromator. The measured intensity ratios of the silicon monochromator to the diamond monochromator were 1.9 and 1.4 at 6.2 and 9.7 keV, respectively. The theoretical calculations for perfect crystals (Blasdell et al., 1995) predict a ratio of 1.6 at 6.2 keV and 1.9 at 9.7 keV. The flux measurements are in reasonable agreement with the calculations and confirm the expected loss in monochromatic beam flux.

The high heat load diamond program has shown that a water-cooled diamond monochromator will perform well even under the highest heat loads on an APS undulator beamline. The drawbacks are the inherent reduction in flux compared to a silicon monochromator and the lack of perfect diamond single crystals of appropriate size. Even so, a diamond monochromator might prove a good choice for certain user applications. Working with Harris Diamond Corp., we have topographed many large uncut stones. This information is available to APS users to assist in their diamond selection. The high heat load team is also participating in an APS/ESRF/SPring-8 collaboration with Sumitomo to develop larger, more nearly perfect single crystals for use as synchrotron radiation monochromators.

4.3.5 Cooled Mirrors

Though most beamlines at the APS currently use a monochromator as the first optical element, there are circumstances in which a mirror is the required first optical component. Using a mirror as the first optical element can considerably reduce the thermal load on the downstream optical components (Yun et al., 1992). However, unlike crystal optics, which can be designed to transmit a large fraction of the incident radiation, a substantial portion of the incident power is typically absorbed in a mirror substrate, and so different design approaches must be applied to mirrors as compared with monochromator crystals.

One approach often adapted in high heat load substrate design is the use of very efficient cooling schemes to reduce the temperature rise, and thus the thermal gradients, in the system. Efficient cooling often implies internal cooling, in which case cooling conduits are configured in the optical substrates close to the heated surface to convect the heat away efficiently. Typical cooling schemes used are conventional channel cooling (using millimeter-size channels) (Tonnessen et al., 1996), microchannel cooling, and various enhanced cooling techniques, such as pin-post (Khounsary and Yun, 1996) or porous media cooling. Another approach to high heat load optics design, developed by XFD, is based on the recognition that efficient cooling is not synonymous with optical performance and that the key issue in thermal management is how to minimize undesirable thermal deformations and not how to minimize overall thermal deformations. In other words, the question is not how well to cool but just how to cool. In practice, this understanding leads to interesting design concepts in which location (and not efficiency) of the cooling in the optical substrate is most relevant. Because of the novelty of this design technique, referred to as the optimal contact-cooled design approach, it is briefly described here (Tonnessen et al., 1993).

When a thermally significant x-ray beam impinges on a mirror, the overall mirror distortion can be considered as the combination of several components, the most important of which are bending (an overall bowing of the mirror along it length), beam mapping (a distortion of the optics over the area where the power is absorbed), and a ripple distortion (due to the presence, if any, of internal cooling channels). By selecting external cooling, channel ripple distortions are eliminated. The beam mapping distortions are minimized by saturating the entire length of the optics with the incident beam to avoid sharp lengthwise heat flux falloff. The bending of the mirror is dealt with by applying a reverse thermal moment as illustrated in Fig. 4.39.

Figure 4.39a shows a long, free-standing isothermal substrate having no thermally induced deformation. If it is heated on the reflecting surface by a narrow x-ray beam along its entire length, as illustrated in the cross-sectional view of the substrate (Fig. 4.39b), and cooled on the opposite side, it deforms into an arc. The substrate is then convex (defocusing) because of the through-the-thickness temperature gradient. Now, if the substrate is broken up into three imaginary segments, the central segment, as shown in Fig. 4.39c, is heated on the top surface, while the other two segments, as illustrated in Fig. 4.39d, are cooled on the top. When in contact, the central part tends to deform into a convex shape, while the other two segments, which are now cooler on the top than on the bottom, tend to deform into a concave shape. Thus, with proper design, a thermo-mechanically balanced substrate with no bending is obtained, as shown in Fig. 4.39e. The cooling on the reflecting surface essentially applies a thermal moment
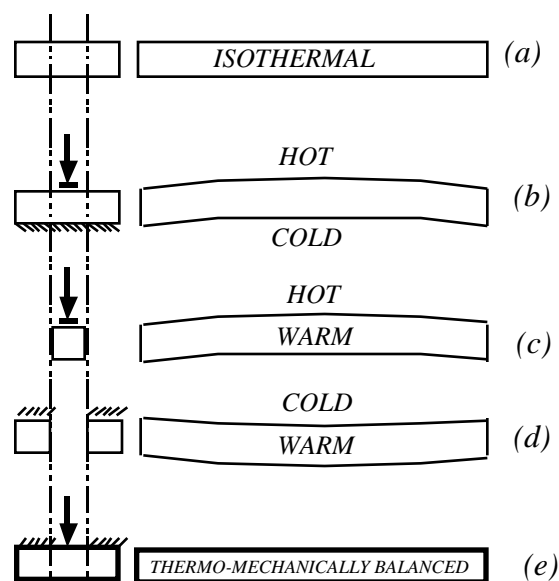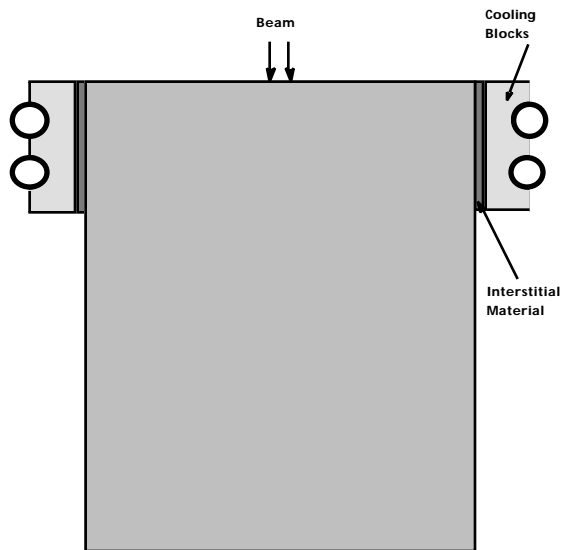

Fig. 4.39 A thermo-mechanically balanced substrate is constructed by optimal selection of the cooling sites. The substrates are shown cross sectionally on the left and longitudinally on the right above.

opposite to that produced by the central segment of the substrate. We refer to this scheme and its variations, devised to restore the desired symmetry to the system, as the reverse thermal moment technique. In actual implementation, cooling pads made of copper are placed in contact with the sides of the mirror flush with the reflecting surface to produce the same effect. This design has several advantages. They include simplicity (no internal channels, no bonding/brazing, no vacuum guards), high reliability (no radiation damage concerns, use of proven materials and techniques, reduced leak potentials), UHV compatibility, low jitter, ease of fabrication and polishing, reduced manufacturing costs, multiplicity of suppliers, and reliable and easy installation and operation. Disadvantages include a longer time constant.

The APS had designed several mirrors based on this approach. One of them, a 1.2-m-long mirror and the first designed on the basis of the reverse thermal moment technique, is cooled by two water-cooled copper plates, 1.5 cm wide and 1.2 m long, pressed against the sides of the mirror flush with the reflecting surface. A thin layer of indium is used to enhance heat transfer from the mirror to the cooling plates. The mirror is made of single-crystal silicon, and is 100 mm wide and 120 mm thick. A schematic of the cross section of that mirror is shown in Fig. 4.40. This mirror has been installed on the undulator A beamline at Sector 2. When the mirror intercepts the beam at 0.3 degrees, the total absorbed power and peak heat flux are about 1200 W and 0.5 W/mm^2, respectively.

Preliminary results on the optical performance of this mirror indicate a maximum steady state slope error of about 7 μrad with undulator gap at 11.9 mm and a beam current of 78 mA. In its final operational configuration, in which an upstream aperture is commissioned and the entire length of the mirror is illuminated with the incident beam at 0.15 degrees angle, a slope error of about 2 μrad is expected. Measurements will be made to evaluate performance.

4.3.6 Other Work Related to Cooled Optics

When the monochromator is placed downstream of the mirror (as described above where a cooled mirror is the first optical component), the crystals will be subject to about 300 W total power and about 4 W/mm^2 peak surface power density (Yun et al., 1992). Experiments using liquid-gallium direct-cooled crystals have shown that they can handle these heat load levels. However, using the reverse thermal moment technique (as described in the "cooled mirrors" section above), we have developed a so-called "U-monochromator" that can handle these power and power density loads with contact cooling (Khounsary et al., 1996). Figure 4.41 schematically shows the U-monochromator. The two main features of the U-monochromator are as follows: (1) by careful consideration of the cooling location and use of the reverse thermal moment technique, the overall bowing along the length can be reduced, and (2) by illuminating the entire length of the crystal along the beam direction, but utilizing only the central part of the beam (as in undulator beams), sharp slope changes in the beam profile and thus in the

Fig. 4.40 A schematic of the cross section of the side-cooled mirror. Water-cooled copper blocks are clamped to both sides of the mirror with a thin layer of indium between the copper blocks and the single-crystal silicon mirror. The cooling blocks provide the thermal gradients to counteract the bending forces of the heat deposited by the incident beam.
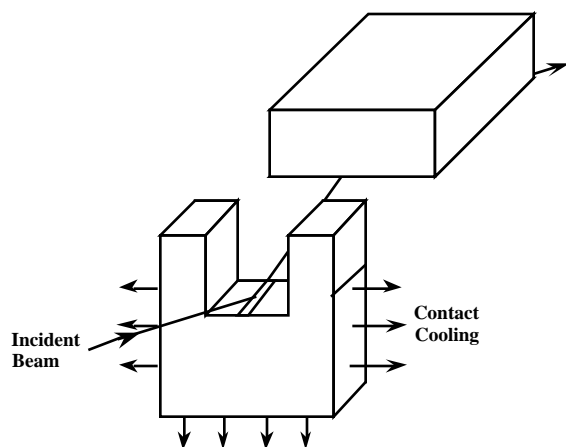
U-Monochromator

A Thermo-Mechanically Balanced Design
Based on the Inverse Thermal Moment Technique

**Contact
Cooling**

**Incident
Beam**

Fig. 4.41 The U-monochromator is shown schematically as the first crystal in a double-crystal arrangement. The crystal is (externally) cooled from the sides and bottom. The beam is allowed to illuminate the entire length of the crystal for optimal performance.

crystal slope errors are avoided. The latter feature is particularly suited to undulator beams because the central cone of the radiation is much smaller than the power envelope of the beam. The U-monochromator has been tested at the 1-ID beamline at the APS. The results are encouraging and show that, indeed, the measured thermally induced slope errors of the contact-cooled U-monochromator are comparable to those of direct liquid-gallium-cooled slotted crystals for the same power loading. The contact-cooled U-monochromator has the advantages of low cost; easy fabrication, mounting and mani-folding; and low maintenance.

While the major effort of the high heat load group has been to study possible solutions for the undulator thermal problem, work has also been performed to provide solutions for the thermal problems on BM beamlines. Although the thermal problems of the BM beamlines are not as severe as those of the ID beamlines, it is still necessary to provide sufficient cooling to the crystals. The goal here is to provide a low-cost and convenient solution to the BM thermal problem. Results from computer simulations performed in 1996 suggest that indirectly water-cooled silicon crystals may perform as well as directly water-cooled ones. Tests of indirectly cooled silicon crystals are currently underway. The present scheme is to have the silicon crystals in contact with a cooled copper block. An indium-gallium eutectic layer is used to facilitate the heat transfer between the silicon and the copper block. The use of indirectly cooled crystals greatly simplifies the crystal mounting/manifolding and the vacuum integrity issues. The simplicity of the crystals and the use of water as the coolant (in the copper block) greatly reduce the cost.

Another program currently underway is the experimental determination of thermal contact resistance across interfaces using various interstitial materials, typically gallium, gallium-based alloys, silver, or indium. This information is used in the design of contact-cooled substrates, such as the contact-cooled mirrors and the diamond monochromators.

We have also looked into the use of liquid gallium as a coolant for synchrotron-radiation optics. Although currently not planned for use on undulator lines, liquid-metal-cooled optics may be important in other applications because of the ability of liquid metal to remove large quantities of heat. A dc current driven pump, based on NdFeB permanent magnets, has been developed by XFD and is now commercially available. The fact that this pump is driven by electromotive forces and has no moving parts minimizes maintenance and makes for easy operation.

A key tool in the design and analysis of all the cooled optical components described above is finite element analysis (FEA). When anchored to previous experimental results, FEA allows us to accurately predict the performance of new optical designs without the costly and time-consuming process of building and testing prototypes.

4.3.7 The Double-Crystal Monochromator Design

The development of the technical specifications for the mechanics of a double-crystal monochromator (DCM) was undertaken by XFD early in the project. When the original specifications were written, the cooling approach for the crystals had not been finalized, and, therefore, the specifications of the monochromator had to be compatible with any of the potential approaches. The underlying philosophy behind the performance specifications of this DCM was to fabricate a device that would be useful to as many APS users as possible; that is, the design should be as generic as possible. In other words, the design should be capable of operating on both BM and ID beamlines (with appropriate changes to the cooling and crystals) with both flat and inclined crystal geometries and with a variety of coolants. The DCM should also have good scanning capabilities in the classical energy range of about 4 to 20 keV with Si (111) crystals. Within the 4 to 20 keV operational range of the DCM, windows can be used to isolate the storage-ring vacuum from the DCM and so it was specified as a high vacuum (10^{-7} to 10^{-8} Torr) device. The impetus for this choice was to facilitate crystal changes, to reduce the effort and time for design, and to keep the overall cost of the system at a reasonable level.

While several different DCM designs are being successfully used at first- and second-generation synchrotron sources, it should be noted that, because of the unique characteristics of the APS, the requirements for the APS DCM are in general more stringent. It is useful to elaborate on some of these differences. For instance, the radiation exposure levels and hardness of the radiation were expected to be significantly higher, owing to the higher energy of the particle beam (7 GeV) than at lower energy storage rings. Discretion in the selection of the materials used inside the DCM was important. The amount of heat generated from Compton scattering off the first crystal was also a concern, and care must be exercised in the mechanical design to minimize the heating of the various components, which can cause drifts and stability problems. And finally, owing to the low particle beam emittance and long beamlines, motion resolution requirements for the APS DCMs are more stringent than those at second-generation sources. Details of the APS DCM specification have been published (Lee and Mills, 1993). Figure 4.42 shows the final motion specifications of the DCM. The contract for the DCM was awarded to Kohzu Seiki in Japan,
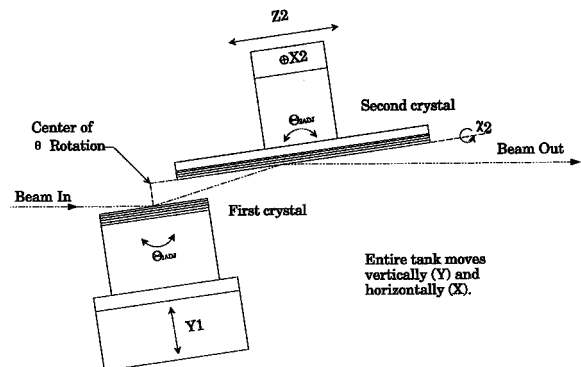

Fig. 4.42 Schematic showing all the motions of the Kohzu DCM. Almost all motions, except the overall tank motions (X and Y), are in vacuum.

and the DCM itself, which has two symmetric crystals, was delivered to the APS in January 1994. After off-line tests and waiting for the necessary beamline construction, the DCM was installed in the beamline in 1995. The technical specifications developed for the first DCM have been used for subsequent procurements of DCMs by SRI-CAT and have served as templates/references for many of the other APS CATs.

The DCM, as delivered by Kohzu Seiki, allows for room-temperature coolants to be brought in on-axis, through the main rotation shaft. It does not, however, allow for liquid nitrogen in these feedthroughs. Liquid nitrogen is brought in (and out) through two auxiliary flanges and flexible hoses inside the DCM, between the flanges and the crystal, that allow for smooth crystal motions. Tests show that this configuration does not degrade the performance of the DCM. The DCM and the liquid-nitrogen pump have been successfully integrated into the beamline and have been performing satisfactorily since the beginning of 1996.

In addition to the more standard DCM configuration described above, with two symmetric crystals, investigations are underway on an alternative two crystal monochromator design. For example, the so-called variable asymmetric monochromator uses two crystals with an 18 degree asymmetric cut (see Fig. 4.43). The crystals are mounted in a manner that allows one to rotate both the first and the second crystal around three separated perpendicular axes corresponding to the angles , which controls the Bragg angle; , which controls the asymmetric-cut angle and the incident beam angle relative to the surface of the crystal; and , which controls the shape of the footprint of the beam on the crystal

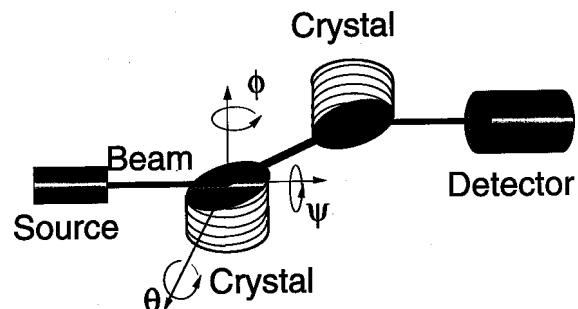*Fig. 4.43 A schematic of the variable asymmetric DCM showing the three orthogonal rotations of the first crystal.*

surface. Rotation around the   axis simultaneously increases the effective asymmetric-cut angle and decreases the incident angle of the beam on the surface of the crystal with no change in the Bragg angle to first order. This allows the area of the beam footprint on the crystal to be altered, changing the thermal load per unit area, and at the same time varies the angular acceptance of the crystal for diffraction for a given incident wavelength. In practice, this allows one to increase the throughput of a narrow band of wavelengths by a factor of 10 to 20 while at the same time increasing the ratio of the area of the footprint of the beam on the crystal to the area of the incident beam by a factor of 50. The second crystal has a similar set of rotation stages and can be moved both perpendicular and parallel to the beam direction. A detailed description of the operation of this kind of monochromator has been published (Smither and Fernandez, 1994).

4.3.8 Brilliance/Brightness Measurements

High heat load monochromator tests have shown that indirectly cooled diamond or direct

cryogenically cooled silicon crystals have negligible thermal distortion under the heat load generated from APS undulator A. These results are based on double-crystal rocking curves that indicate minimal (<1 arc second) thermal distortions due to the heat load. While these measurements are very useful, they do not provide direct information regarding the monochromatic beam brilliance (photons/sec/ eV/mrad^2/mm^2) or brightness (photons/sec/ eV/mrad^2). Because it is the beam brilliance that exemplifies the third-generation synchrotron sources, we have embarked on a program to directly measure the monochromatic beam brilliance. This direct measurement of the beam brilliance is of particular importance to APS users who are interested in beams with very small angular and energy spread, for example, for use in inelastic scattering or nuclear resonant scattering. For such users, beam brilliance is a factor in selecting a monochromator. For a similar (hkl) reflection, the monochromatic throughput (photons/sec) of silicon is about twice that of diamond. However, the energy spread of the monochromatic beam from silicon is about twice that of diamond. For perfect crystals, therefore, theoretically, beam brilliance over a narrow energy range (E) is about the same for both silicon and diamond. Because the cost and maintenance of a cryogenic system is much higher than that of a water-cooled diamond, it is important that we measure the actual beam brilliance from these two systems. The measurement scheme (see Fig. 4.44a) involves two channel-cut crystals in a dispersive (+,-,-,+) geometry downstream of the DCM. Using asymmetric (43° asymmetry) silicon (777) reflection in the channel cuts, the acceptance of such a four-bounce reflection at 14.5 keV is about 2 mrad and 7 meV. With such a small acceptance in angle and energy, it is possible to map out the Dumond diagram of
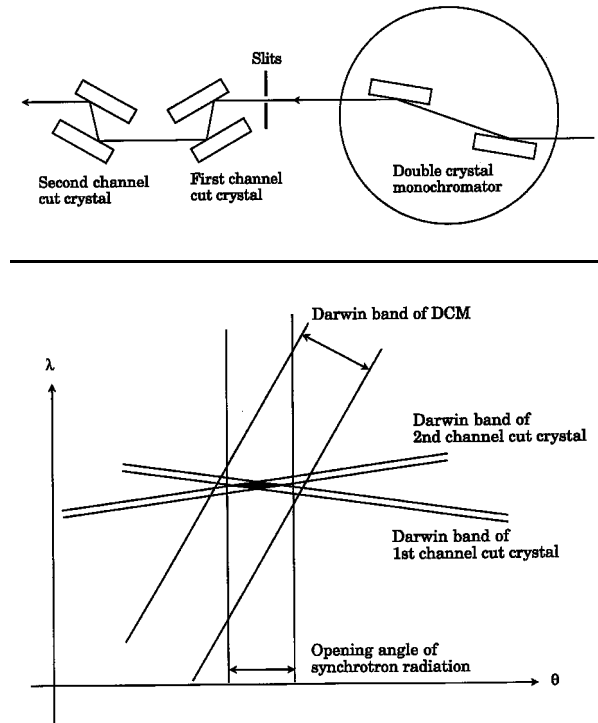

Fig. 4.44 (a) Schematic of the setup for the brilliance measurements. The channel-cut reflections used presently are asymmetrically (43° asymmetry) cut Si(777). (b) Dumond diagram representation of the setup for the brilliance measurements. The dark diamond-shaped region represents the transmission of the two channel-cut crystals. By rotating the channel-cut crystals, the transmission diamond can be moved relative to the rest of the figure. If slits are not used, the beam brightness is measured. As shown, the measurements are only for the vertical direction, integrated over the horizontal direction. The diagram is not to scale.

the monochromatic beam and directly measure the beam brilliance. The Dumond diagram representation of the measurement setup is shown in Fig. 4.44b. Currently, the plan is only to measure the beam brilliance in the vertical direction integrated over the horizontal direction.